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Physics Potential of a Tevatron Tripler

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Abstract

We explore the capabilities for new physics discovery in proton-antiproton collisions at 5.4 TeV center-of-mass energy with luminosity $10^{33}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ at a Tripler upgrade of the Tevatron collider. The prospects are robust for the usual Higgs boson and supersymmetry benchmarks. With an integrated luminosity of 40 fb^{-1}, discoveries at 5σ could be made for a standard Higgs boson of mass $\lesssim$ 680 GeV (600 GeV for 10 fb^{-1}), a lighter chargino of mass $\lesssim$ 380 GeV, and an extra Z boson of mass $\lesssim$ 2.6 TeV; four-fermion contact interactions from new physics with scale $\lesssim$ 74 TeV could be excluded at the 95% confidence level.

I. INTRODUCTION

Recent developments in superconducting magnet design may make it possible to upgrade the Fermilab Tevatron collider at moderate cost by replacing its ring of 4 Tesla dipole magnets by 12 Tesla dipoles [1]. This Tripler design would yield proton-antiproton colliding beams at a center of mass energy $\sqrt{s} = 5.4$ TeV and a luminosity about $10^{33}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, which could significantly enhance the potential for new particle discoveries at the Tevatron. The physics justification for the Tripler requires detailed benchmark studies and comparison with the LHC potential, since the LHC is expected to become operational on a similar time-line as the Tripler. In this Letter we present benchmark results for discovery of the Higgs boson in the Standard Model (SM), the trilepton and same-sign dilepton signals of supersymmetric (SUSY) particles, extra Z-bosons and contact interactions. The interesting range for the SM Higgs boson mass is 102.6 GeV $\lesssim m_H \lesssim$ 550 GeV; the lower value is the current LEP 2 experimental limit [2]; the upper value is due to the requirement of a non-trivial and consistent effective theory [3]. Lattice calculations give a mass bound of $m_H \lesssim$ 710 GeV [4]. Electroweak precision data favor $m_H \lesssim$ 255 GeV at 95% C.L. [5]. The lightest Higgs scalar in minimal supersymmetry (SUSY) is predicted to have a mass less than 130 GeV [6] and our SM analysis applies equally to it in the decoupling limit [7]. Naturalness considerations in the minimal supergravity (SUGRA) model lead to an upper bound on the lighter chargino mass of $m_{\chi_1^\pm} \lesssim$ 400 GeV [8].

We show below that the Tevatron Tripler with $\mathcal{L} = 40\ \mathrm{fb}^{-1}$ would provide at least a 5σ discovery for the SM Higgs boson up to $m_H = 680$ GeV and for the lighter chargino up to $m_{\chi_1^\pm} = 380$ GeV.

II. HIGGS BOSONS

The Tevatron Tripler has great potential for the Standard Model Higgs boson search. In Fig. 1(a) we show the fusion cross section from $gg \to H$ as well as $VV \to H$, and the associated production $p\bar{p} \to VH + X$ at $\sqrt{s} = 5.4$ TeV, where $V = W^\pm, Z$. For comparison, we also show the cross sections at the Tevatron Run II ($\sqrt{s} = 2$ TeV) and the LHC for some representative Higgs boson masses. The scale on the right-hand side gives expected number of events for 10 fb^{-1} integrated luminosity. We see that the total cross sections for Higgs production are increased by about an order of magnitude at the Tripler compared to the Tevatron Run II. As a remark, if the Tripler is running at the pp mode, the $gg \to H$ cross section would not change; that for $VV \to H$ would be reduced by about 10% and that for $q\bar{q} \to VH$ by about 25%.

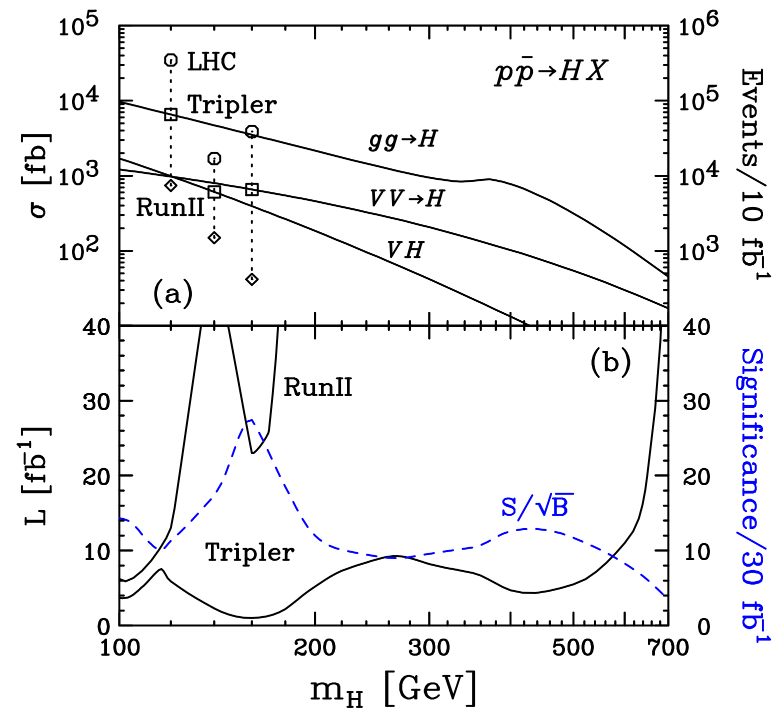

FIG. 1. (a) The Higgs boson production cross section via gluon fusion, vector-boson fusion and associated production processes versus m_H at a 5.4 TeV Tripler. Also shown are representative production cross sections at the Tevatron Run II (diamond), the Tripler (square) and the LHC (circle). (b) The required integrated luminosity to reach 5σ statistical significance versus m_H (solid curves). The lower and upper curves correspond to the Tripler and the Tevatron Run II respectively. (The Tevatron curve is taken from the Run II Higgs Boson Working Group report [9]). Five channels (see text for details) have been combined for the Tripler discovery curve. The dashed curve gives the signal significance $S/\sqrt{B}$ at the Tripler for 30 fb^{-1} (the right-hand scale).

For a Higgs boson mass $m_H < 130$ GeV, it is known that the leading signal at the Tevatron is $p\bar{p} \to W^{\pm}H \to \ell^{\pm}b\bar{b}X$ [10]. However, this channel becomes less accessible at the LHC because of the much larger QCD background. We studied this process at the Tripler and found that it is a useful channel to reach 5σ significance for $m_H \lesssim 120$ GeV with a luminosity of less than 8 fb^{-1}.

For the intermediate range mass Higgs boson ($125 \lesssim m_H \lesssim 220$ GeV), the most important discovery channel is the signal of dileptons along with missing transeverse energy ($\not{E}_T$) through the process $p\bar{p} \to gg \to H \to WW^* \to \ell\bar{\nu}\bar{\ell}\nu$ ($\ell = e$ or μ). The leading background is WW production. We impose kinematic cuts similar to those in [11] and find that this mode has a 5σ statistical significance reach for $120 \lesssim m_H \lesssim 220$ GeV (assuming $\mathcal{L} = 20$

fb^{-1}). In comparison, at the Tevatron Run II with $\mathcal{L} = 30$ fb^{-1}, a 5σ significance can be reached only at the narrow mass range near $m_H \simeq 160$ GeV [11].

When $m_H > 2m_Z$, the "gold-plated" channel $H \to ZZ \to 4\ell$ becomes interesting. After the basic acceptance cuts and a search for a peak in the four-lepton invariant mass distribution, this channel has a good signal to background ratio, $S/B \sim 1$; for example, with $m_H = 220$ GeV, the signal and background cross sections are 1.2 fb and 1.5 fb, respectively.

For a still larger Higgs boson mass, the "silver-plated" channel $H \to ZZ \to \ell\bar{\ell}\nu\bar{\nu}$ is more useful since its rate is 6 times larger than the 4ℓ rate, although Higgs boson mass reconstruction is more difficult because of the missing neutrinos. The irreducible background is ZZ production. After suitable cuts on $\not{E}_T$ and the $M_C(\ell\ell, \not{E}_T)$ cluster transverse mass, we find the 5σ discovery reach for m_H is about 500 GeV for $\mathcal{L} = 20$ fb^{-1}.

For a Higgs boson mass $m_H \gtrsim 500$ GeV, the $H \to WW \to \ell\nu jj$ channel can also be used. The leading background is the Wjj QCD process. We find that 5σ discovery reach of this channel can be achieved for $m_H \approx 650$ GeV for $\mathcal{L} = 20$ fb^{-1}.

In Fig. 1(b), we plot the 5σ mass reach for Higgs boson discovery at the Tripler from combining the above channels (the lower solid curve). With $\mathcal{L} = 20$ fb^{-1}, a 5σ Higgs boson discovery would be possible over the entire mass range from the current limit of 102.6 GeV all the way up to 650 GeV. In comparison, with $\mathcal{L} = 30$ fb^{-1}, the Tevatron Run II (the upper solid curve) can only cover a very limited range of the Higgs boson masses, *i.e.*, $m_H < 130$ GeV and $m_H \simeq 160$ GeV. The dashed curve gives the signal significance $S/\sqrt{B}$ at the Tripler for 30 fb^{-1}. It is important to see that for $m_H < 200$ GeV we should be able to achieve more than 10σ significance via $WH(\to b\bar{b})$ and $gg \to H \to WW$, both involving the electroweak gauge coupling WWH. We note that further improvement of the reach at the Tripler is possible by optimizing acceptance cuts and by including the ZH channel as well as channels involving tau-leptons in the final states. To summarize, the Tevatron Tripler offers a tremendous opportunity to discover the SM Higgs boson over the mass range from the current bound to ~ 650 (680) GeV, for $\mathcal{L} = 20$ (40) fb^{-1}.

III. SUPERSYMMETRIC PARTICLES

A large number of production processes for supersymmetric particles have been experimentally investigated at the Tevatron, yielding lower mass limits for strongly interacting gluinos,

squarks, especially stops, and weakly interacting sleptons and neutralinos/charginos [12]. The signals of supersymmetric particles are trileptons from chargino/neutralino pairs, same-sign dileptons from gluino pairs and missing transverse energy carried by the lightest neu-

tralino.

Figure 2 shows that the Tripler cross sections are considerably larger than those for the Tevatron Run II [13]. The gluon fusion contribution to SUSY particle production at $\sqrt{s} = 5.4$ GeV is more important than that of quark-antiquark annihilation. The fractions of SUSY particle production from incoming gluons at the given SUGRA point are 67% for stops and 72% for gluino pairs at the Tripler, while they are only 25% and 10% for Run II. This affects the K factors due to SUSY-QCD corrections through the larger color charge of the radiating incoming partons.

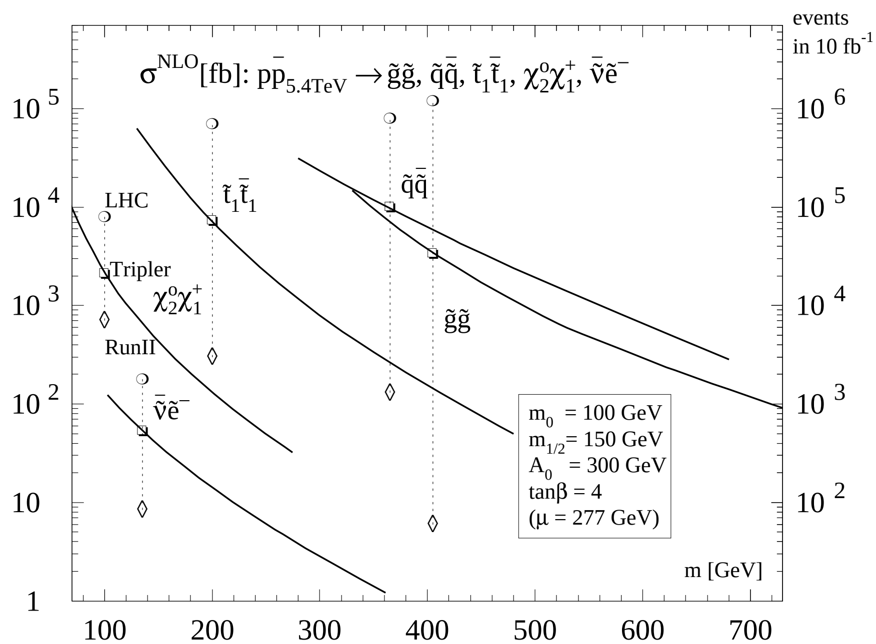

FIG. 2. Some next-to-leading order pair production cross sections versus the (smaller of the two) final state masses. The vertical bars indicate the SUGRA inspired scenario and show the respective cross sections at the Tevatron Run II and the LHC.

To assess the discovery potential of the Tripler in searching for SUSY particles, we present results from simulations for the trilepton and the same sign dilepton (SS2L) signals with an event generator and a simple calorimeter including our acceptance cuts. The ISAJET 7.40 event generator program [17] with the parton distribution functions of CTEQ3L [18] is employed to calculate the trilepton ($3\ell + \not{E}_T$) and the same sign dilepton (SS2L) signals from all possible sources of SUSY particles. The backgrounds from $t\bar{t}$ is calculated with ISAJET as well.

The trilepton signature with missing transverse energy ($3\ell + \not{E}_T$) is one of the most promising channels to search for supersymmetric particles [14]. At the Tevatron with $\sqrt{s} =$ 2 TeV, the major source of trileptons is the associated production and decay of the lighter chargino ($\chi_1^\pm$) and the second lightest neutralino (χ_2^0) [15,16]. At the Tripler, gluinos and

squarks can be the dominant source of trileptons and same-sign dileptons along with jets in the final states, while $\chi_1^\pm\chi_2^0$, and the slepton pair production processes $\tilde{\ell}^*\tilde{\ell}$, and $\tilde{\ell}\tilde{\nu}$ generate clean trilepton events.

Requiring $p_T(\ell_{1,2,3}) > 20, 15, 10$ GeV, $|\eta(\ell_{1,2,3})| < 1, 2, 2$, and applying other acceptance cuts [15], we find that the major SM backgrounds are (i) $q\bar{q}' \to WZ + W\gamma \to \ell\nu\ell\bar{\ell}$ or $\ell'\nu'\ell\bar{\ell}$ ($\ell = e$ or μ) (ii) $q\bar{q}' \to WZ + W\gamma \to \ell\nu\tau\bar{\tau}$ or $\tau\nu\ell\bar{\ell}$ and subsequent τ leptonic decays, with one or both gauge bosons being virtual. We employed the programs MADGRAPH [19] and HELAS [20] to evaluate the background cross section of $p\bar{p} \to 3\ell + \not{E}_T + X$ for contributions from all these subprocesses. Additional backgrounds come from production of $t\bar{t}$ and $ZZ \to \ell\bar{\ell}\tau\bar{\tau}$ [15,16]. At the Tripler with 20 fb^{-1} integrated luminosity, we expect about 36 background events; a 5σ signal would have 30 events. If the Tripler runs with pp collisions, the major trilepton background cross section will be reduced by about 35% and the SUSY trilepton signal cross section will be reduced by about 18%, 27%, 55% and 59% for $m_{1/2} = 140$, 200, 300 and 460 GeV, respectively.

Figure 3(a) presents the cross sections at the Tripler for trileptons with jets and for *clean* trileptons with 0 or 1 jet at the Tripler versus $m_{1/2}$, for $\tan\beta = 3$, $m_0 = 100$ GeV, and $\mu > 0$. Also shown is the cross section for a 5σ signal with $\mathcal{L} = 40$ fb^{-1}. The trilepton signal will be observable up to $m_{1/2} = 470$ GeV ($m_{\chi_1^\pm} \sim 380$ GeV, $m_{\tilde{g}} \sim 1.1$ TeV) with $\mathcal{L} = 40$ fb^{-1}, which is a great improvement from the Tevatron Run II reach of $m_{1/2} \lesssim 260$ GeV ($m_{\chi_1^\pm} \sim 195$ GeV, $m_{\tilde{g}} \sim 600$ GeV) with $\mathcal{L} = 30$ fb^{-1} [15].

Same-sign dileptons with missing energy (SS2L) is another promising channel to search for supersymmetry [21–23]. The cross section of the SM background in this channel is very small after suitable cuts. There are several major sources of the SS2L signal: (i) $\tilde{g}\tilde{g}$ production, where $\tilde{g} \to \chi_1^\pm + q\bar{q}'$ and $\tilde{g}\tilde{g} \to \ell^\pm\ell^\pm + \text{jets} + \not{E}_T$; these can test the Majorana property of the gluinos if $m_{\tilde{g}} < m_{\tilde{q}}$. (ii) $\tilde{g}\tilde{q}$; (iii) $\tilde{q}\chi^\pm$; (iv) $\bar{q}\bar{q}$ where $\tilde{q} \to q'\chi_1^\pm$; and (v) trilepton events where one of the leptons is lost.

For same-sign dilepton events having $p_T > 15$ GeV [$p_T > 10$ (20) GeV for the Tevatron (LHC)] and $|\eta_{1,2}| < 1, 2$, we require at least two jets as well as the same isolation and missing energy as in the trilepton analysis. The major SM backgrounds are (i) $WZ \to \ell\nu\tau\bar{\tau}$, (ii) $t\bar{t}$ and (iii) ZZ. The contributions from WW, $W +$ jets and $Z +$ jets are negligible after cuts [22,23]. With $\mathcal{L} = 20$ fb^{-1} at the Tripler, we expect about 14 background events; a 5σ signal would have 19 events. In pp collisions at $\sqrt{s} = 5.4$ GeV, the major same-sign dilepton background cross section from $WZ \to \ell\nu\tau\bar{\tau}$ will be reduced by about 30% and the SUSY same-sign dilepton signal cross section will be about the same as that in $p\bar{p}$ collisions.

In Fig. 3(b), we present the cross sections after cuts versus $m_{1/2}$, for same-sign dileptons with $\tan\beta = 3$, $m_0 = 100$ GeV, and $\mu > 0$. This signal is observable up to $m_{1/2} = 300$ GeV

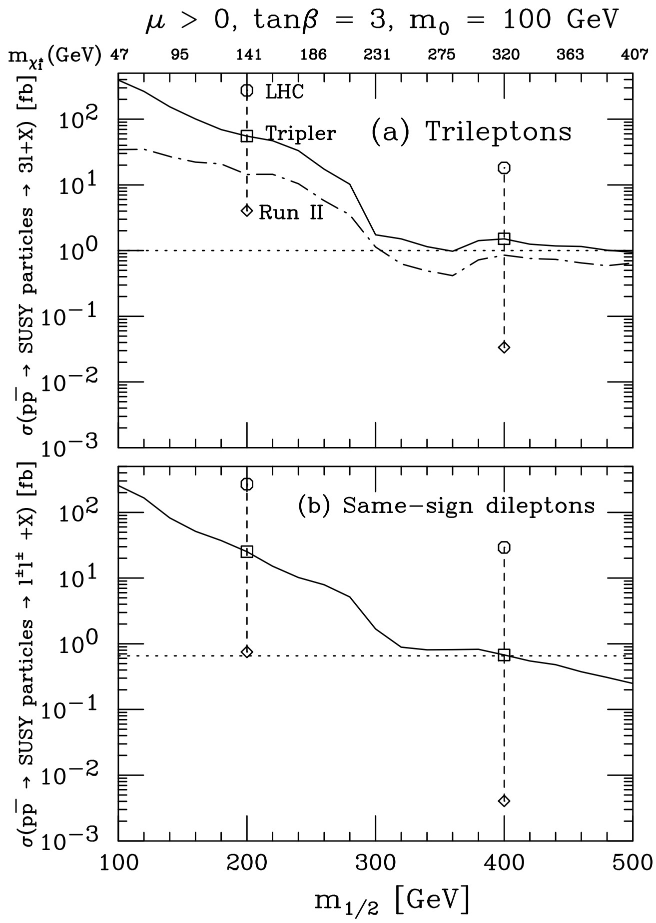

FIG. 3. Cross sections of $p\bar{p} \to$ SUSY particles $\to 3\ell{+}X$ and $p\bar{p} \to$ SUSY particles $\to \ell^\pm\ell^\pm{+}X$ after cuts, versus $m_{1/2}$, at $\sqrt{s} = 5.4$ TeV, with $\mu > 0$, $\tan\beta = 3$, $m_0 = 100$ GeV, for (a) inclusive trileptons (solid) and clean trileptons (dash-dot), and (b) for same-sign dileptons with at least 2 jets (solid). Also shown are the cross sections at the Tevatron Run II (diamond) and the LHC (circle). The dotted horizontal lines denote the 5σ signal cross sections for $\mathcal{L} = 40$ fb^{-1}.

($m_{\chi_1^\pm} = 250$ GeV, $m_{\tilde{g}} = 780$ GeV) with $\mathcal{L} = 20$ fb^{-1}, and can be improved up to $m_{1/2} = 400$ GeV ($m_{\chi_1^\pm} = 320$ GeV, $m_{\tilde{g}} = 960$ GeV) with $\mathcal{L} = 40$ fb^{-1}. Other SUSY signals from single lepton+ $\not{E}_T$ and $\not{E}_T$+jets, which are promising at the LHC [22], may also be useful at the Tripler.

IV. CONTACT INTERACTIONS AND EXTRA Z-BOSONS

Many sources of new physics at high scales can be parameterized by four-fermion contact interactions [24,25],

$$L_{\rm NC} = \sum_q \sum_{\alpha,\beta={\rm L,R}} \frac{4\pi\epsilon}{(\Lambda_\epsilon^{\alpha,\beta})^2} \left(\overline{e_\alpha}\ \gamma_\mu e_\alpha\right) \left(\overline{q_\beta}\ \gamma^\mu q_\beta\right) \tag{1}$$

where $\epsilon = \pm 1$ and Λ is the typical energy scale at which the new physics sets in. The Drell-Yan process of lepton pair production at hadron colliders is a powerful tool to probe the contact scale of new physics contributions [25]. In this process the contact terms interfere with γ and Z exchanges, yielding multi-TeV sensitivities to contact scales Λ. The 95% C.L. lower limits on VV contact scales that can be set are

$$\begin{array}{lll} \text{Tevatron} & (2\ \text{TeV},\ 20\ \text{fb}^{-1}) & \Lambda_+ = 36\ \text{TeV} \\ \text{Tripler} & (5.4\ \text{TeV},\ 20\ \text{fb}^{-1}) & \Lambda_+ = 61\ \text{TeV} \\ \text{Tripler} & (pp\text{: } 5.4\ \text{TeV},\ 20\ \text{fb}^{-1}) & \Lambda_+ = 34\ \text{TeV} \\ \text{LHC} & (14\ \text{TeV},\ 100\ \text{fb}^{-1}) & \Lambda_+ = 84\ \text{TeV} \end{array} \tag{2}$$

The comparative reach for other contact terms is similar. With $\mathcal{L} = 40$ fb^{-1} at the Tripler, contact interactions from new physics with a mass scale $\lesssim 74$ TeV could be excluded at 95% C.L.

Additional Z-bosons are a generic feature of gauge symmetries larger than the SM. We consider two interesting models with extra Z bosons: (i) Z'_χ in SO(10) $\to$ SU(5) $\times$ U(1)$_\chi$, and (ii) Z'_S in the sequential standard model, with SM coupling strength to quarks and leptons while couplings to W and Z bosons are suppressed. The interactions of the extra Z bosons with fermions are given by [26]

$$\mathcal{L} = -g_2 \sum_i \bar{\psi}_i \gamma^\mu (\epsilon_{iL} P_L + \epsilon_{iR} P_R) \psi_i Z'_\mu, \tag{3}$$

where $P_{L,R} = (1 \mp \gamma_5)/2$, $g_2 = \sqrt{5/3}\sin\theta_W g_1$, and $g_1 = e/(\sin\theta_W \cos\theta_W)$. In the sequential standard model, the coupling constant in Eq. (3) is replaced by g_1 and $\epsilon_{L,R}$ are the same couplings as those of the SM Z boson. We find that the 5σ reach limits are

$$\begin{array}{ll} \text{Tevatron} & M_{Z'_\chi} = 1.1\ \text{TeV},\ M_{Z'_S} = 1.2\ \text{TeV} \\ \text{Tripler} & M_{Z'_\chi} = 2.6\ \text{TeV},\ M_{Z'_S} = 2.9\ \text{TeV} \\ \text{Tripler } (pp) & M_{Z'_\chi} = 2.0\ \text{TeV},\ M_{Z'_S} = 2.1\ \text{TeV} \\ \text{LHC} & M_{Z'_\chi} = 5.1\ \text{TeV},\ M_{Z'_S} = 5.3\ \text{TeV}. \end{array} \tag{4}$$

The energies and luminosities of the colliders are the same as those in Eq. (2). Thus, the Tripler would more than double the Z'_χ reach of the Tevatron and have about half the reach of the LHC.

V. CONCLUSIONS

Our analyses of physics benchmarks show that the Tripler offers robust opportunities for the exploration of new physics. This is dramatically the case for the SM Higgs sector where we find that with 40 fb^{-1}, a 5σ discovery can be made up to a Higgs mass of 680 GeV, thus covering the theoretical interesting mass range for the SM Higgs boson. In particular, a luminosity of 30 fb^{-1} would lead to more than 10σ signal significance for $m_H < 200$ GeV via the gauge coupling channels WH and $gg \to H \to WW$, directly probing the coupling of the gauge and Higgs bosons. Supersymmetry searches at the Tripler via trileptons would extend up to a chargino mass $m_{\chi_1^\pm} = 380$ GeV, which is close to the naturalness upper bound. The scale of contact interactions can be pushed by more than 20 TeV above the expected reach of the Tevatron and extra Z bosons could be discovered up to a mass 2.6 TeV.

Our comparisons of the Tripler and LHC shows that although the LHC has a greater new physics discovery reach in most channels, the Tripler can cover the interesting mass range for the SM Higgs and also offers coverage for most of the lighter chargino mass range expected from naturalness considerations. Thus, for the Higgs and chargino benchmarks both the Tripler and LHC may offer comparable physics opportunities.

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REFERENCES

[1] P. McIntyre, E. Accomando, R. Arnowitt, B. Dutta, T. Kamon, and A. Sattarov, hep-ex/9908052.

[2] P. McNamara, talk presented at the LEPC meeting, September (1999).

[3] T. Hambye and K. Riesselmann, Phys. Rev. D **55**, 7255 (1997); C. Quigg, Acta Phys. Polon. **B30**, 2145 (1999); and references therein;

[4] J. Kuti, L. Lin and Y. Shen, Phys. Rev. Lett. **61**, 678 (1988); U.M. Heller, M. Klomfass, H. Neuberger and P. Vranas, Nucl. Phys. **B405**, 555 (1993).

[5] J. Erler and P. Langacker, hep-ph/9809352.

[6] Y. Okada, M. Yamaguchi and T. Yanagida, Prog. Theor. Phys. **85**, 1 (1991); H. Haber and R. Hempfling, Phys. Rev. Lett. **66** (1991) 1815; J. Ellis, G. Ridolfi and F. Zwirner, Phys. Lett. B **257**, 83 (1991); R. Hempfling and A.H. Hoang, Phys. Lett. B **331**, 99 (1994); M. Carena, M. Quiros, C.E.M. Wagner, Nucl. Phys. **B461**, 407 (1996); H. Haber, R. Hempfling and A. Hoang, Z. Phys. **C75**, 539 (1997); S. Heinemeyer, W. Hollik, G. Weiglein, Phys. Rev. D **58**, 091701 (1998); R.-J. Zhang, Phys. Lett. B **447**, 89 (1999).

[7] H. Haber and Y. Nir, Nucl. Phys. B335, 363 (1990).

[8] G.W. Anderson and D.J. Castano, Phys. Rev. D **52**, 1693 (1995); K.L. Chan, U. Chattopadhyay and P. Nath, Phys. Rev. D **58**, 096004 (1998).

[9] Physics at Run II Workshop – Higgs Bosons, http://fnth37.fnal.gov/higgs.html.

[10] A. Stange, W. Marciano and S. Willenbrock, Phys. Rev. D **49**, 1354 (1994); Phys. Rev. D **50**, 4491 (1994).

[11] T. Han and R.-J. Zhang, Phys. Rev. Lett. **82**, 25 (1999); T. Han, A. Turcot and R.-J. Zhang, Phys. Rev. D **59**, 093001 (1999).

[12] Physics at Run II Workshop – SUGRA, http://fnth37.fnal.gov/sugra.html.

[13] W. Beenakker, R. Höpker, M. Spira and P.M. Zerwas, Nucl. Phys. **B492**, 51 (1997); W. Beenakker, M. Krämer, T. Plehn, M. Spira and P.M. Zerwas, Nucl. Phys. **B515**, 3 (1998). H. Baer, B.W. Harris, and M. Hall Reno, Phys. Rev. D **57**, 5871 (1998); W. Beenakker, M. Klasen, M. Krämer, T. Plehn, M. Spira and P.M. Zerwas, hep-ph/9906298, to appear in Phys. Rev. Lett.

[14] D.A. Dicus, S. Nandi and X. Tata, Phys. Lett. B **129**, 451 (1983); A.H. Chamseddine, P. Nath and R. Arnowitt, Phys. Lett. B **129**, 445 (1983); H. Baer, K. Hagiwara and X. Tata, Phys. Rev. D **35**, 1598 (1987); P. Nath and R. Arnowitt, Mod. Phys. Lett. A **2**, 331 (1987).

[15] V. Barger, C. Kao, T.-J. Li, Phys. Lett. B **433**, 328 (1998), V. Barger and C. Kao, hep-ph/9811489, to appear in Phys. Rev. D; and references therein.

[16] H. Baer, M. Drees, F. Paige, P. Quintana and X. Tata, hep-ph/9906233; K. Matchev and D. Pierce, hep-ph/9907505.

[17] F. Paige and S. Protopopescu, in *Supercollider Physics*, ed. D. Soper (World Scientific, 1986); H. Baer, F. Paige, S. Protopopescu and X. Tata, in *Proceedings of the Workshop on Physics at Current Accelerators and Supercolliders*, ed. J. Hewett, A. White and D. Zeppenfeld, (Argonne National Laboratory, 1993), hep-ph/9305342; *ISAJET 7.40: A Monte Carlo Event Generator for* $pp, \bar{p}p, \mathrm{and} e^+e^-$ *Reactions*, Bookhaven National Laboratory Report BNL-HET-98-39 (1998), hep-ph/9810440.

[18] H.L. Lai *et al.*, Phys. Rev. **D51**, 4763 (1995).

[19] MADGRAPH, by T. Stelzer and W.F. Long, Comput. Phys. Commun. **81**, 357 (1994).

[20] HELAS, by H. Murayama, I. Watanabe and K. Hagiwara, KEK report KEK-91-11 (1992).

[21] V. Barger, W.-Y. Keung, and R.J.N. Phillips, Phys. Rev. Lett. **55** 166 (1985); R.M. Barnett, J. Gunion and H. Haber, Phys. Lett. B **315**, 349 (1993).

[22] H. Baer, C. Chen, F. Paige and X. Tata, Phys. Rev. D **53**, 6241 (1996).

[23] H. Baer, C. Chen, M. Drees, F. Paige and X. Tata, Phys. Rev. D **58**, 075008 (1998).

[24] E. Eichten, K. Lane and M.E. Peskin, Phys. Rev. Lett. **50**, 811 (1983).

[25] V. Barger, K. Cheung, K. Hagiwara and D. Zeppenfeld, Phys. Lett. B **404**, 147 (1997); Phys. Rev. D **57**, 391 (1998).

[26] For reviews, see M. Cvetič and P. Langacker, in *Perspectives in Supersymmetry*, G.L. Kane (ed.), World Scientific, Singapore, 1998; J.L. Hewett and T.G. Rizzo, Phys. Rept. **183** 193 (1989).